APPLICATION OF MAGNETIC AMPLIFIERS TO ELECTRONIC COMPUTERS

JOHN DAVID DAVIDSON

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J. D. DAVIDSON

APPLICATION OF MAGNETIC AMPLIFIERS TO ELECTRONIC COMPUTERS

by

John David Davidson,
Lieutenant, United States Navy

Submitted in partial fulfillment
of the requirements
for the degree of
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PREFACE

Reliability has become a limiting factor in construction and operation of complex electronic equipment. This thesis was undertaken to investigate the possibility of replacing the primary source of this unreliable operation, the electron tube, in one of the most complex of all equipments the electronic computer. It is intended to show the reader that the magnetic amplifier is no longer a useless gadget of days gone by, but a real competitor to the once supreme vacuum tube.

The author wishes to express his gratitude to Mr. L. Black and Mr. W. Bowen of Acme Electronics Inc., Pasadena, California for their assistance in understanding the problems and potentialities of magnetic amplifiers.

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LIST OF SYMBOLS AND ABBREVIATIONS

C	Capacitance
E_{ac}	A.C. Voltage
E_s	Signal Voltage
I	Current
IF	Intermediate Frequency
L	Inductance
MAG/AMP	Magnetic Amplifier
NFB	Negative Feedback Back
NI	Ampere Turns
R	Resistance
RF	Radio Frequency
V	Voltage
V_o	Output Voltage

CHAPTER I

INTRODUCTION

As electronic equipment becomes more complex the problem of reliability is fast becoming the limiting factor in the operation of that equipment. It has been reported that over 50% of equipment failures are due to tube faults, even when ruggedized tubes are used. As the number of tubes used increases, the reliability of the equipment approaches that of the electron tube itself[*]. The tube is a very fragile device. The presence of the heater element and critical spacings, makes it prone to fail under the effects of shock and vibration. The heater element and cathode materials suffer from the effects of aging and gasing in a rather unpredicatable manner. In computer service, operation involving long periods under cut-off conditions has proven fatal to a tremendous number of tubes. The heat generated by the heater elements of electron tubes requires that ventilation be provided. This heat represents a vast reduction in the efficiency of the device. Variations in the supply voltage varies the cathode emission and can greatly shorten the life of the heater element. It is, therefore, logical to investigate the possibility of replacing the tube, at least in part, in an effort to overcome these handicaps.

The ideal replacement for the tube, would have none of the defects and all the advantages of the electron tube. It would be shock resistant, free from aging effects, uneffected by power supply fluctuations and over-loads, contain no heater elements, be more efficient, and capable of prolonged operation under cut-off conditions. In order to completely

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[*] Stanford Research Institute Terminal Report November 1950

replace the tube, this replacement must still possess high gain, fast response, and high input impedance. In order to increase reliability, this ideal device would contain no moving parts, but rather it would be completely static.

One device which fulfills virtually all of the above requirements, for many applications, is the magnetic amplifier. Once discarded as a slow, cumbersome, inefficient device, the magnetic amplifier is returning as a real competitor to the vacuum tube. Since it is not a direct replacement for the tube, special circuits must be evolved to utilize its inherent advantages and minimize its disadvantages. As these circuits, and new materials, are developed, the magnetic amplifier more nearly approaches the ideal replacement requirements.

Though lacking some of the advantages of the electron tube, the magnetic amplifier has the outstanding attribute of reliability. Its life span is basically comparable to that of an equivalenty rated transformer. When rectifiers are used, their aging determines the service-free life. Selenium and germanium diodes available today, when operated within their ratings, can be expected to give 60,000 hours of reliable service (27). This is far in excess of the reliability attainable with electron tube circuits. This potential improvement in reliability, in itself, is sufficient cause to investigate the possibility of replacing electron tube circuits with magnetic amplifiers. The possibility of combining magnetic amplifier and electron tube circuitry should not be overlooked. The elimination of only a portion of the tube circuits will still improve the reliability problem.

Though discovered over fifty years ago, and appearing in the literature by name as early as 1916 (1), the magnetic amplifier has been long forgotten by the electronic engineer. The advent of the vacuum tube, with its faster response and apparently more efficient operation completely over-shadowed the use of saturable devices. An American invention*, such devices have been used in power work in the United States since the turn of the century. It was Germany, however, that realized the possibilities of reliability offered by the magnetic amplifier in other fields. During World War II the Nazis expended millions of dollars on the development and study of the magnetic amplifier. Improved core material and the selenium rectifier allowed them to develop circuits equal in many respects to the tube itself. These circuits were used in the field in a great variety of applications, previously using only tubes, both military and civilian.

At the completion of the war the United States got an insight into the possibilities of the Mag/Amp by examining the German Cruiser Prinz Eugen which used several in her fire control systems. Her log showed that no servicing had been required for ten years. It is this potential saving of technical personnel that interests our Armed Forces today, particularly the Navy. Many contracts are in progress to extend the use of magnetic amplifiers into every field of electronic engineering, including computers.

In order to illustrate how this device can be applied to a complex system, the electronic computer has been chosen. Computers have grown to such size as to be inoperative as much as 50% of the time, in some

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*U.S. Patent 720,884 17 February 1903, Burgess and Frankenfield

cases. "Unscheduled engineering time" as high as 70% has been reported (24). This is certainly a field in which reliability is a necessity. The circuits to be given and discussed are some of the basic types suitable for both analog and digital computer use. No overall computer is considered, though complete computers using only magnetic amplifiers are possible. One analog type, at least, is now in production, and several are under design. The limitations of the magnetic amplifier are pointed out, but it is shown that they do not negate the usefulness of these circuits for many computer applications. To aid in understanding the operation and construction of these circuits a chapter on the theory of operation, and another of the methods of design are included.

CHAPTER II

THEORY OF OPERATION

The magnetic amplifier has acquired many forms and names in its long history. In this paper only three types will be discussed as fundamental to understanding the operation of saturable core devices. Many other circuits have advantages over these basic circuits. However their operation is similiar to one or the other of the types given. In the later chapters some of these circuits will be presented.

1. The Neutral Type

The simplest type of Magnetic Amplifier is the neutral type, or simple saturable reactor, (8) (10). It consists of two magnetic circuits with a "gate" or power winding on each. The magnetic circuits may be combined on a single core, such as an 'E' core, or on separate cores, such as toriods. The two winding are connected in either series or parallel and the combination placed in series with an a.c. source and the load. A d.c. "control" winding is common to both circuits. This winding is connected so that no current is induced in it from the gate winding by transformer action. This can be seen by referring to Figure 2-1. The arrows on the cores indicate the instantaneous flux set up by the gate windings. Application of the right hand rule shows that the currents induced in the control circuits oppose one another. Actually, even harmonic components of the power frequency can appear on the control winding (3). They do not change the average value of d.c. applied unless a rectifier element is in the circuit. When there is no rectifier element, or when the impedance of the control voltage source is made very high, these harmonics have no effect.

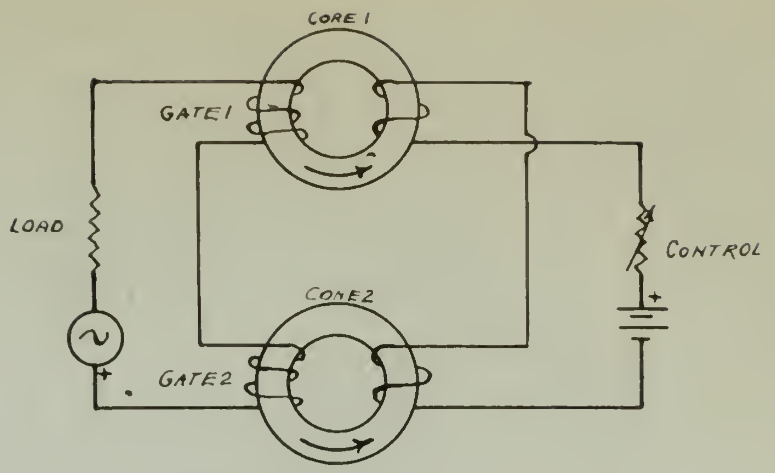

FIGURE 2-1 SERIES CONNECTED NEUTRAL MAGNETIC AMPLIFIER

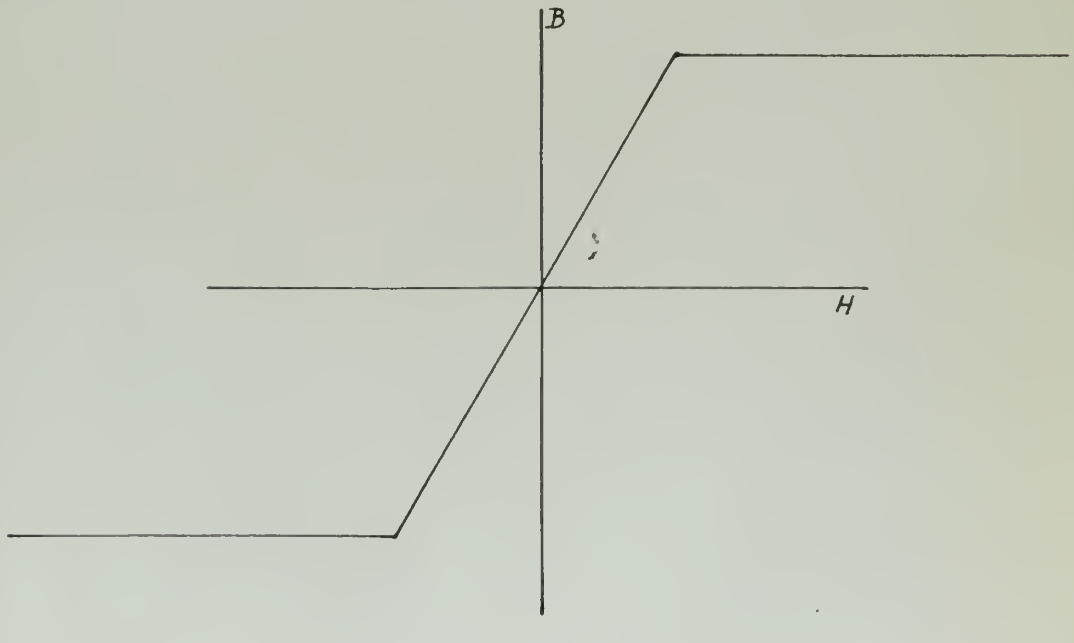

FIGURE 2-2 IDEAL MAGNETIZATION CURVE

If a perfect magnetization curve, such as that in figure 2-2, is assumed, there will be no flux as the voltage passes through zero. If no control voltage is applied, and the gate has sufficient turns, the a.c. voltage never reaches the knee of the curve in either direction. Since the core has a high permeability, almost all the voltage appears across the gate, and only the magnetizing current flows through the load. When a direct current is passed through the control winding, in either direction, the average value of flux moves the operating point either up or down the magnetization curve.

If the polarities shown in figure 2-1 are assumed for the first half cycle, it can be seen from the diagram that the d.c. current flowing in the control circuit sets up an aiding flux in core 1 while the flux is opposing the instantaneous flux in core 2. As the sine wave of voltage applied to the gates increases, core 1 will reach its saturation flux density at some value of voltage. When this occurs, the permeability of the core suddenly drops to the permeability of air and remains there for the rest of the half cycle. The magnetization current to this core is increased at this point, known as the "firing angle", and thus the current through the load is increased. The opposing fluxes set up in core 2 during this time prevent it from reaching saturation. During the next half cycle, the instantaneous flux set up in each core by the gate windings are reversed. The d.c. flux thus aids in core 2 and opposes in core 1. The operation is repeated with core 2 saturating. Changing the value of d.c. current applied to the control winding varies the firing angle, hence the average current applied to the load. The transfer

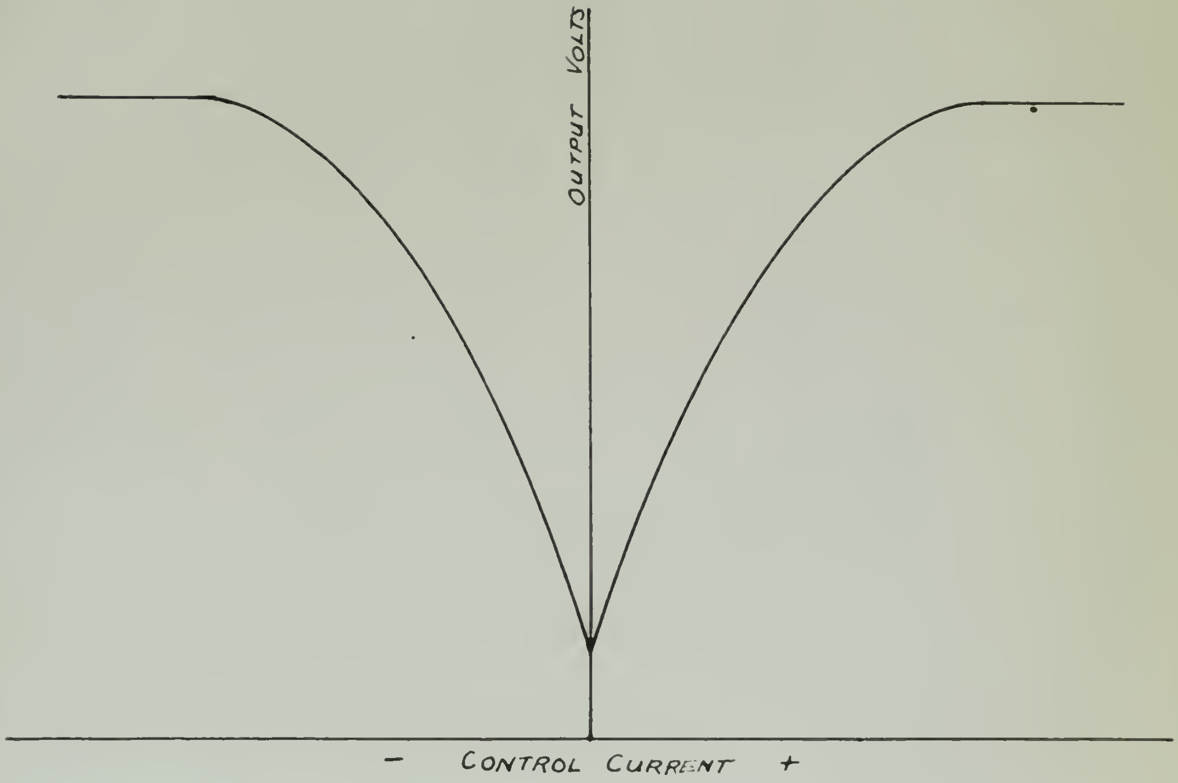

FIGURE 2-3 TRANSFER CHARACTERISTIC OF NEUTRAL TYPE MAGNETIC AMPLIFIER

Characteristic of this type of magnetic amplifier is shown in figure 2-3.

2. Application of Positive Feedback

When positive feedback is applied to the circuit of figure 2-1, the operation is completely changed (11) (12). This feedback may be applied in the form of either voltage or current as shown in figures 2-4 and 2-5. Other configurations are also possible.

The first effect, noted on the application of feedback, is that the device is no longer "neutral", i.e. the direction of current through the control winding is important. Next, when no control current is applied, the output is no longer minimum, but approaches the maximum. These phenomena are illustrated in figure 2-6. Also in figure 2-6 it will be noted that increasing the number of feedback turns increases the Slope of the transfer curve. When enough turns are used the Mag/Amp becomes "bi-stable", i.e. possesses two states. The bi-stable condition, as shown by figure 2-6, is one of either "off" or "on" operation. One value of control voltage switches the Mag/Amp off while another less negative value switches it on. There are no stable operating points in between these two states. The curve of vertical slope represents the highest power gain, since a very small change of control current can shift the output from one extreme of voltage to another. Power gain is defined as the ratio of power supplied to the load to the power applied to the control winding. It is calculated using the load resistance and control winding resistance. Power gain is largely a function of the core material used.

The shift in the operating point may be compensated for by applying

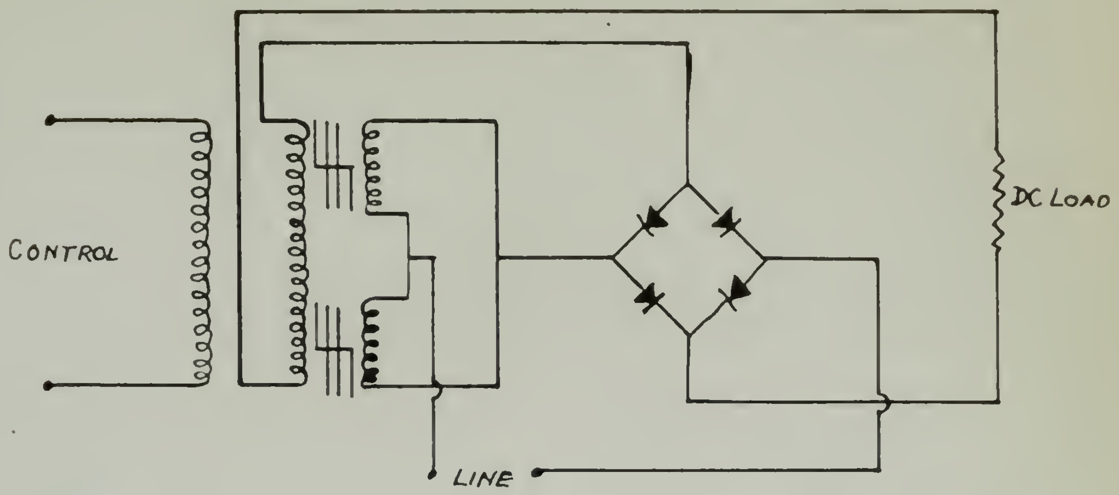

FIGURE 2-4 A CIRCUIT FOR APPLICATION OF POSITIVE VOLTAGE FEEDBACK (PARALLEL CONNECTED MAG/AMP).

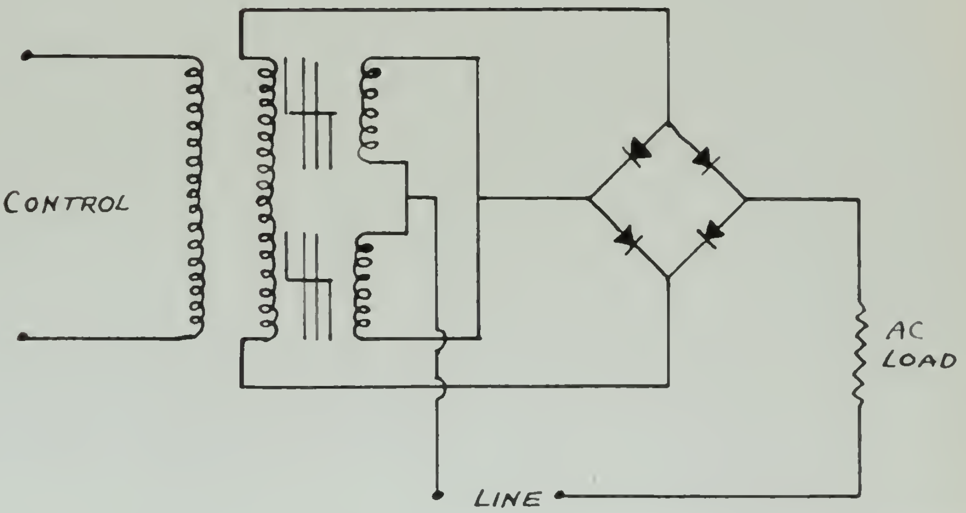

FIGURE 2-5 A CIRCUIT FOR APPLICATION OF POSITIVE CURRENT FEEDBACK AND DC OUTPUT.

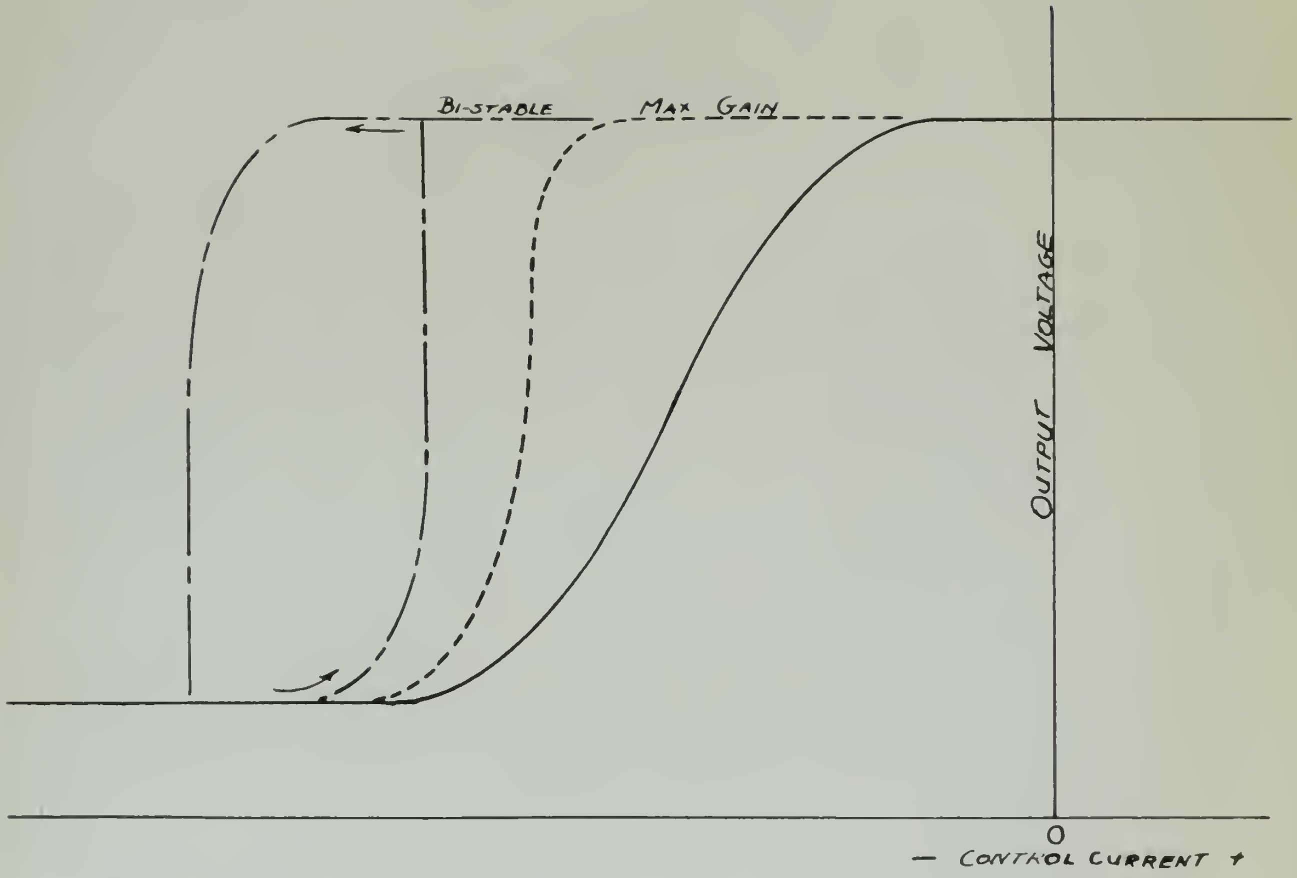

FIGURE 2-6 TRANSFER CHARACTERISTICS OF MAG/AMP WITH POSITIVE FEEDBACK APPLIED

still another overall winding, similiar to the control winding, called "bias". A steady d.c. is applied to this coil as required to place the control signal on the desired portion of the transfer curve.

The number of turns required for each of the above classes of operation may be given as a percent of the gate turns. Approximately 75% of the number of gate turns will be required to obtain the vertical slope, or maximum gain condition. Less will provide a curve between this condition and that of figure 2-3, more will cause a bi-stable condition, increasing with the percent.

Still another phenomena occurs in amplifiers using positive feedback, which is not readily apparent. The feedback circuit is highly inductive, hence a decaying current tends to continue flowing in one set of feedback rectifiers beyond their duty half cycle. At this same time a current is flowing in the other set of rectifiers which are now in their duty half cycle. This simultaneous conduction of all rectifiers is known as "commutation". It may be explained by considering the superimposed sinusoidally varing flux and direct component of flux in the cores (7). This implies the need of even harmonics of magnetomotive forces. In the simple amplifier these components are provided by the even harmonics flowing in the control circuits. In amplifiers employing positive feedback, this need of even harmonics must be contributed by the feedback windings. The contribution of these windings is dictated by the ratios of the number of turns and resistances of the gates and feedback windings and are not necessarily coincident with the even harmonics produced by rectification. This results in an apparent increase

in the ratio of feedback turns to gate turns required.

3. The Self-Saturating type of Magnetic Amplifier

The self-saturating magnetic amplifier or Amplistat* of figures 2-7 is one of the most useful types. The figure is only one of many forms it may take (14). The other circuits operate in a similiar fashion however. By providing a unidirectional flux in each core during alternate half cycles, the effect of positive feedback can be attained without extra feedback windings. This results in better core utilization, since fewer windings are required. In practice, it may be found desireable to also provide positive external feedback. In this case, the turns required to produce a maximum gain transfer characteristic, by means of current feedback, would only be 10% or less of the number of turns required for the gates. Some of the types of amplifiers in this class have been constructed with power gains as high as 10^{12}.

The basic amplifier again consists of two magnetic circuits with a gate winding on each. The rectifiers allow current to flow in one gate on the first half cycle, and the other gate on the next half cycle. An overall control winding is also provided so that no current is induced, as before. If no control is provided, the flux will be zero at the time the input voltage crosses zero. The flux in one core will rise as the voltage rises, as in transient operation. During this time, almost all of the voltage will appear across the gate winding, because of the high permeability of the core. At the time the knee of the magnetization curve is reached, the permeability drops, in a few electrical degrees, to that of air and the load current is increased for the remainder of

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*General Electric Trademark

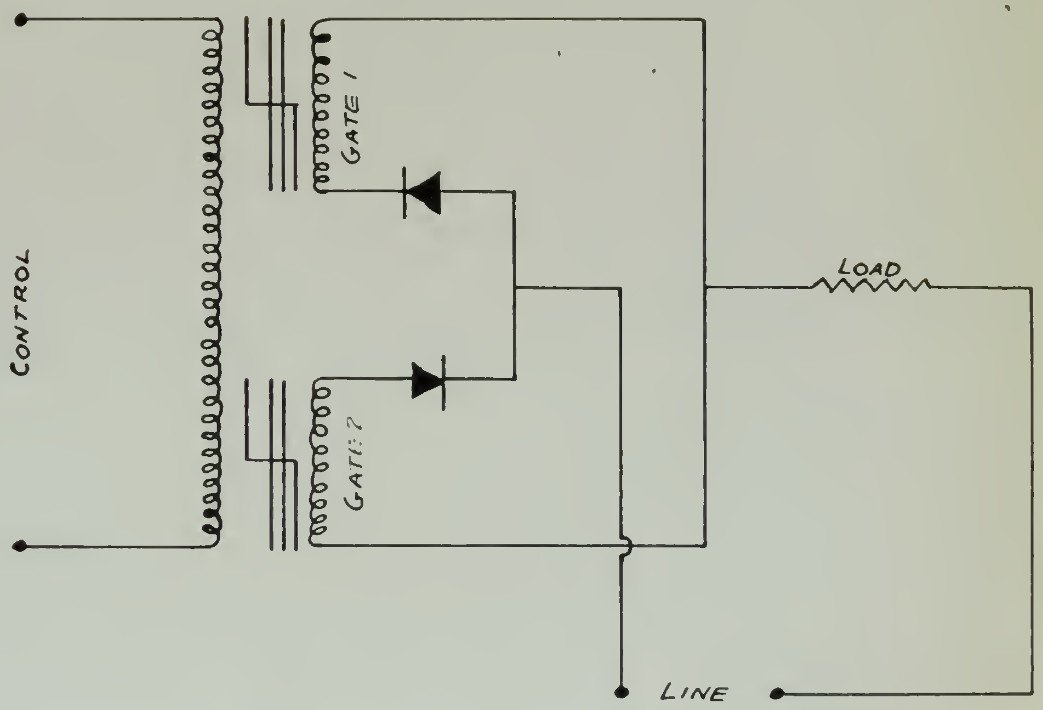

FIGURE 2-7 SELF-SATURATING MAG/AMP

that half cycle. On the negative half cycle, the other gate repeats the operation. Applying control current shifts the firing angle as before.

In this type of operation, it is important that the two cores saturate at corresponding points on the positive and negative half cycles. In order to do this, it is necessary that the cores used be very closely balanced. Any "back" current flowing through the diodes will tend to demagnetize the cores and reduce amplification. It is therefore necessary that they, also, be balanced, as well as having as high a back resistance as possible. If they do not have a high back resistance, added external positive feedback can be used to compensate for the loss of gain. The actual "spoiling" of diodes by a shunting resistance is sometimes used, together with external positive feedback, to reduce the effects of diode back leakage change with age and temperature.

In general, the core material and diodes being used determine the transfer characteristics. In figures 2-8 and 2-9, the characteristics of two otherwise identical amplifiers are shown using two different core materials. (In this case, 1DU laminated configuations*.) These curves, taken by the author, also illustrate the effects of added external positive feedback and shunting the diodes with a resistance. The circuit used was that of figure 2-10. This type of positive feedback is known as the "Cross-over" type.

To position the control point on the transfer curve, a bias winding would usually be necessary with this type circuit. Commutation also takes place in the self-saturating mag/amp, just as in the previous type. It is compensated for with external positive feedback, as shown above.

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*Magnetic Metals Corp. Cores

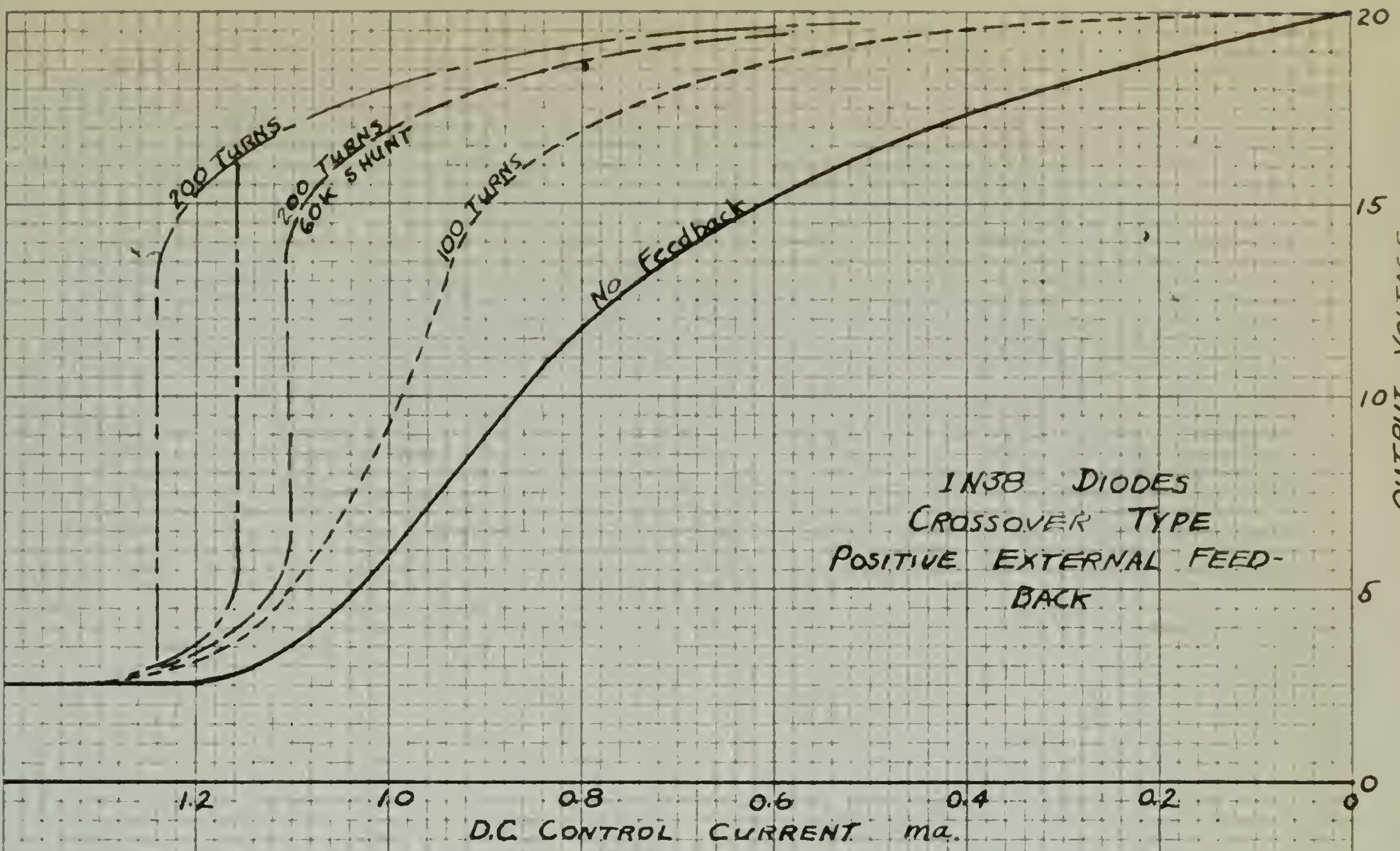


FIGURE 2-8 SELF-SATURATING MAG/AMP CHARACTERISTICS (WITH "49 METAL" CORES)

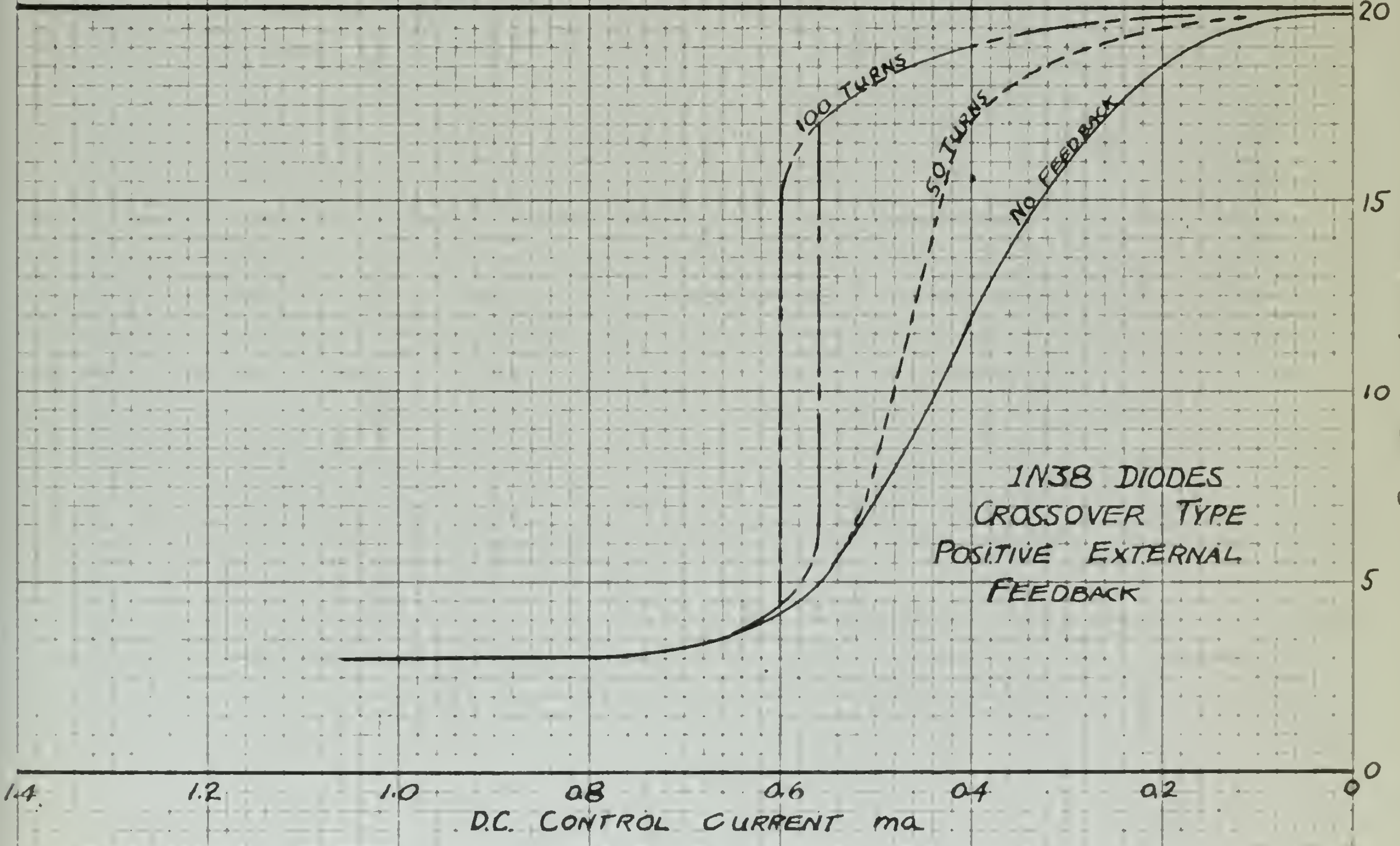


FIGURE 2-9 SELF-SATURATING MAG/AMP CHARACTERISTICS (WITH "HYMU" CORES)

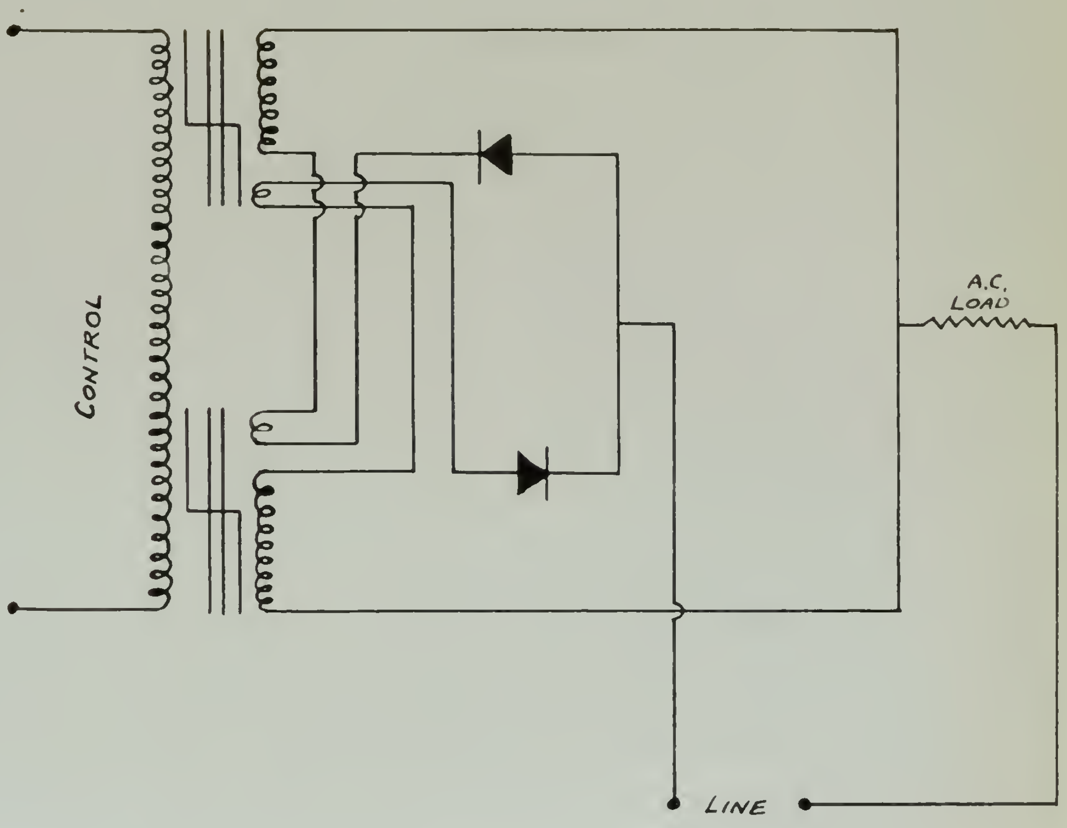
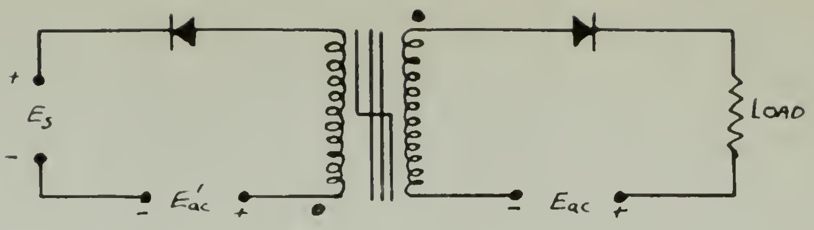


FIGURE 2-10 CIRCUIT USED TO OBTAIN CURVES OF FIGURES 2-8 AND 2-9

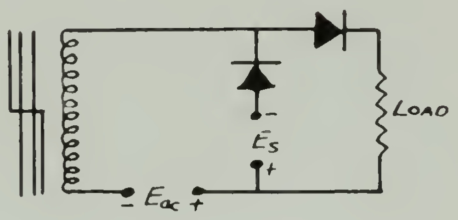
4. The Single-Core Magnetic Amplifier

A new type of magnetic amplifier has been developed known as the Single-Core type (17) (18). The development of this device is based upon the recognition that magnetic amplifiers are voltage sensitive rather than current sensitive. Two types of this basic amplifier are shown in figure 2-11. For most applications, the two winding type, shown in figure 2-11(a), offers the greatest versatility, since it isolates the input and output circuits, so it will be considered. The operation of both types are similiar, however, and the single winding type would often be useful in less demanding designs.

The operation of the circuit is quite simple. If the core is considered saturated initially, with the polarities indicated in figure 2-11, current can flow only in the control or reset winding because of the presence of the rectifiers. This causes the core to come out of saturation an amount dependent upon the relative amplitudes of the signal and the supply voltage. In the next half cycle, current can flow only in the gate circuit. The gate proceeds to saturate at a firing angle dependent upon the previous reset half cycle. The response is, then, once per cycle of power frequency. If the two units are used in push-pull configurations, the rate can be increased to twice per cycle of power frequency.



(a) TWO WINDING TYPE



(b) SINGLE WINDING TYPE

FIGURE 2-11 SINGLE-CORE MAGNETIC AMPLIFIERS

CHAPTER III

PRACTICAL DESIGN

Optimum operation of a magnetic amplifier depends upon proper selection of the core. The dimensions, proportions and magnetic characteristics all effect the performance of the completed device (9). The proper selection of the core, for a particular application is largely a matter of experience. The data supplied by manufacturers is, in general, incomplete, and unless extensive tests are conducted on a large selection of available material optimum design can not be affected. At the present time, all the high performance materials are not readily available, and those that are available are quite expensive. The uniformity of core materials from one lot to the next leaves something to be desired. It is, therefore, a basic policy of most concerns in the field to restrict their designs to only a very few types of core materials. This is a matter of economics. Perhaps, as the use of magnetic amplifiers and uniformity of materials increases, the industry will provide handbooks of characteristics similiar to those provided for electron tubes. When this is done, the design of magnetic amplifiers may graduate from an art to a science.

The procedures for design are not standardized, each company adopting its own. One procedure calls for the use of a family of H vs B curves, and the use of a load line not unlike the procedures used with tube characteristics (2). The construction of the family of curves is time consuming, however, and the load line is not a straight line. The load line is only defined at the end points, in fact and is usually elliptical in shape. For improved core materials in which some simplifying assumptions are valid, a method of obtaining the steady-state

characteristics using dimensionless curves has been developed (7). These methods are too involved for consideration here.

The design can be computed mathematically to a first order approximation (6) (21) (23). This requires knowing the cross sectional area of the core, and the saturation flux density. This information is generally furnished by the manufacturer of the core. The values furnished, however, are average and may not apply to the cores on hand. It should be noted that the dimensions of a toriod can not always be measured easily. Some of the better materials possess magnetostrictive properties and are, therefore, enclosed in a nylon case which allows the necessary degrees of freedom for proper operation. The external dimensions of the case do not represent the dimensions of the core.

A very simple, yet satisfactory, empirical design procedure involves the measurement of the voltage required to just saturate the actual cores to be used. In order to make this measurement, a few turns are placed on the core and the hysteresis loop of the reactor is viewed on an oscilloscope by means of a circuit similiar to that shown in figure 3-1. The applied voltage at the desired frequency is increased until the point of saturation is reached. Knowing this voltage, and the number of turns, the volt per turn ratio can be calculated. The voltage across the twenty ohm resistor in figure 3-1 represents the magnetization and loss currents. (a measure of quality)

The volt/turn and turn/volt ratios, as well as, the control NI required for reducing the output of an Amplistat type circuit to a minimum, also determined experimentally, are given in the Appendix for Deltamax*

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*Arnold Engineering Company, Chicago, Ill.

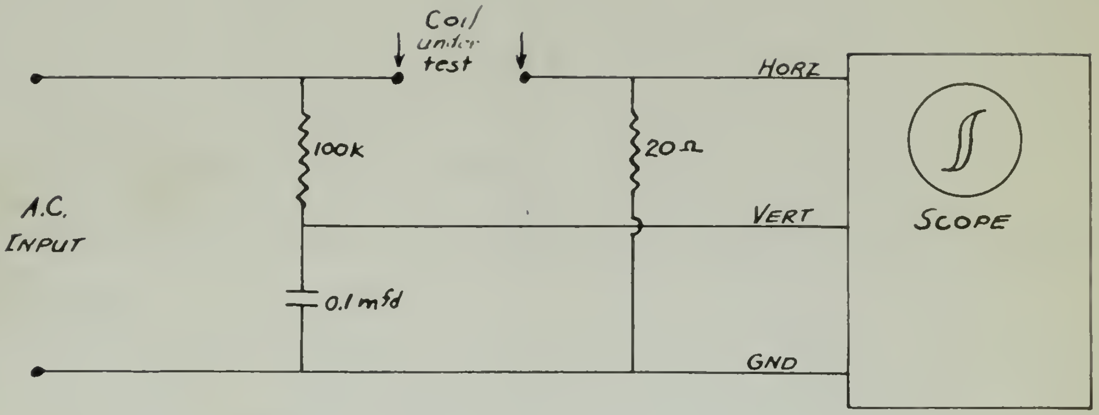

FIGURE 3-1 CIRCUIT FOR OBTAINING HYSTERESIS LOOP OF CORE MATERIAL

toriods currently available.

Once the volt/turn ratio is known, it is a simple matter to determine the required number of turns for the gate winding. It is necessary to know only the required range of operation, i.e. the upper and lower values of the desired transfer characteristic. If the difference between these two limits is, say, 25 volts, the gates are provided with 25 volt windings. The number of turns is simply the required voltage times the turns/volt for that core. The size of wire to be used is calculated from the allowed d.c. resistance, using the wire tables, on the basis of a mean turn, which can be approximately measured. The allowed d.c. resistance of the winding is usually taken as 10% or less of the load resistance.

The control winding is calculated from the current to be used and the NI value given for that core size. Usually, it is desirable to keep the control turn equal to, or less than, the gate turns because of the time constant involved. The bias winding is calculated on the same basis, remembering that the NI given is the total required to reduce the output to zero.

The utilization of the iron is important for efficiency. This demands maximum copper for the size window available, allowing for insulation and a hole large enough to complete the winding. The square inches of window used by the copper can be calculated from the standard wire tables (which give turns/square inch). Allowing 10% for insulation and a hole large enough to accommodate the shuttle to be used, the required window can be compared with the available window as given in the

Appendix. It may be necessary to carry through these simple calculations several times to find the proper core size.

The selection of rectifiers should not be based entirely on the specifications furnished by the manufacturer. They must be considerably derated, and balanced. Balanced pairs can be obtained only by checking the forward and reverse currents, under several load conditions, of a number of rectifiers. The highest possible back resistance is desirable to obtain maximum gain as explained in Chapter II. For long life and stability the rating of the rectifiers must be quite conservative, to be consistent with the long life of the reactor itself. The instability of the rectifier is the largest contributing factor to temperature drift and noise. Another factor to be considered is the wide variety of waveforms applied to rectifiers in mag/amp circuits (5). A general rule of thumb, which has proven satisfactory in rating selenium diodes for these applications, is 10 to 15 volts back voltage per cell, rather than the manufacturers rating of 26 to 40 volts per cell.

Diffused junction germanium power diodes are now becoming available. Their characteristics seem very well suited to Mag/Amp application, except for poor stability as regards temperature. Over normal ambient temperature ranges, both types of diodes give stable operation when the reverse voltage per cell is held to a low value (such as 10 volts per cell for selenium). Normal operation with Selenium, at least, can be attained over the range of -40° to 100° Centigrade by considerably derating the rectifiers with respect to both leakage and forward current.

Other factors to be considered in choosing rectifiers are their

frequency ratings and capacitance. These factors are most generally of interest at higher frequencies where lower level stages are being considered. The diodes most often used for such applications are the smaller germanium types.

CHAPTER IV

COMPUTER CONSIDERATIONS

In Chapter I it was pointed out that the ideal replacement for the electron tube must fulfill certain requirements as well as provide improved reliability. The long life of magnetic amplifiers has been discussed and shown to be superior to the electron tube. It now remains to discuss the limitations and advantages of the mag/amp as applied to the general field of electronic computers.

1. The Time Constant of a Magnetic Amplifier

As with any L and R circuit a time constant is involved with a magnetic amplifier. The maximum theoretical response time would be 63% rise in one half cycle of line frequency based on the conventional log response curve. A magnetic amplifier is not simple, however, and the time constant depends upon many things. For example, it is known that the time constant is proportional to the power gain. For certain applications this points up a limitation of the conventional magnetic amplifier. This limitation is not as serious as it may sound, however. The response is obviously inversely proportional to the supply frequency. For faster response time, the power frequency need only be increased. With new core materials, now available, responses in the microsecond region are possible, using high frequency power sources. For most anolog computer applications, then, the time constant is not a limiting factor.

The response of the single-core type makes it extremely useful to the computer field (19). Where 100% change of state is desired, as in digital computers, three to six cycles must pass before full output is

even approached with the conventional circuit. With the single-core type, full output is reached one half cycle after the applied pulse. The response, then, is fast and discrete. The response time in this circuit has been shown, by Ramey, to be independent of the inductance of the reactors and, therefore, constant (17) (18). Both of these facts make the single-core mag/amp a logical choice for digital computers where operation is basically "on" or "off". The discrete half cycle delay is also useful in the digital computer field as will be shown in the next chapter where circuits are presented. Increasing the power frequency of this circuit greatly increases the speed. Operation of single-core digital computer elements in the megacycle range is quite feasible with high frequency cores now available.

2. Input Impedance

The input impedance of a magnetic amplifier is relatively low compared to that of an electron tube. This is apparent, since a mag/amp must draw current to operate. Nevertheless, input impedances as high as one megohm can be attained. For most computer applications this is not too low. In those analog input circuits that can not accept this much loading, a tube can be used to control the mag/amp. This technique can still result in improved reliability by reducing the number of tubes used.

3. Frequency Response

The frequency response of magnetic amplifiers is of interest in analog computer applications. At the present time the upper frequency

limit is about a half megacycle. This limit is imposed by the winding capacitance and core losses. For this response a power frequency on the order of 5 megacycles is required. Further development of core materials may improve this limit. Additional work on the single-core type may greatly increase the upper range.

Even with this rather low frequency response, a large number of analog computer applications are possible. The majority of such applications require frequency responses in the audio region.

4. Efficiency

The efficiency of a magnetic amplifier is fundamentally high. Since it is reactive in operation, it absorbs only the power required by its core losses and winding resistances. The diodes also possess a resistive drop. The mag/amp contains no wasteful heater and requires only a low power d.c. bias supply. It, therefore, has an efficiency greater than the electron tube. Since there is little heat generated, there is generally no ventilation problem, except for higher power units. In this case, the rectifiers sometimes require ventilation.

5. Environmental Conditions

The mag/amp can usually be placed for life in an hermetically sealed can, and built into the equipment as are other components. This affords complete protection against shock, vibration and humidity. The effects of temperature, as was pointed out in Chapter III, are not serious when proper diodes are choosen. The mag/amp is far superior to the electron tube with respect to environmental conditions. In general, it may be stated that the mag/amp is no more subject of its environment than any equivalent transformer.

In the case of toroidal wound units, this is even more the case, since the effect of stray magnetic fields have less effect on the closed magnetic circuits.

6. Other Considerations

It has been stated that uniformity of cores is a problem in construction of magnetic amplifiers. The uniformity does vary from lot to lot, or even from core to core. This is not a serious problem, however, as the difference is quite small. After an initial design has been placed in production the correction becomes simple. The usual toriodal wound mag/amp consists of two cores. The gates are placed on a large number of cores, then the hysteresis loops are checked. The cores are then divided into closely matched pairs, stacked and the over-all windings wound to complete the amplifier.

Matching of rectifiers on a unit in production is generally done by the diode manufacturer. The units arrived ready for installation. Most diode manufacturers have a complete line of rectifiers, parallel to their commercial line, which are "rated and balanced for Mag/amp service".

The cost of core materials and rectifiers are quite high, compared to the electron tube, at present. There is no direct figure on this, since the size of the unit is a factor. The smaller units, for the higher frequencies, very nearly approach the cost of the equivalent tube. Mass production would certainly place the mag/amp on a competitive basis with the electron tube as far as cost is concerned.

The uniformity of the completed mag/amp, considering the cores, rectifiers and cost, would be well within the tolerances held for electron

tubes. In some cases where a vertical slope transfer characteristic is essential, critical circuit adjustments may be necessary. These would be no more involved than many adjustments on conventional tube circuits. For example, R.F. and I.F. adjustments can seldom be made using one tube and then be expected to be correct for another, even though the same type tube is used.

The effects of aging, as has been pointed out, are largely associated with diode aging. The aging of the core materials has little effect on performance when the unit is hermetically sealed. It has very recently been discovered that core aging is primarily due to humidity (15).

In addition to the points already brought out, there are two additional advantages of the magnetic amplifier over the electron tube. First, there is complete electrical isolation between the input and output circuits. This is an important item in such circuits as d.c. amplifiers. Secondly, the magnetic amplifier requires no warm-up. It is always ready for instant use, since no heaters are required.

To attempt to compare the weight and size of magnetic amplifiers with tubes is rather unfair. The size and weight of the core material required in a mag/amp application is an inverse function of frequency. High speed replacements for tubes in computers are actually smaller and lighter than equivalent tube circuits. For power frequency units this is not generally the case. 60 cycle components may weigh several times as much as their counterparts, though their volume is generally comparable.

CHAPTER V

APPLICATION TO COMPUTERS

Electronic computers today have reached a temporary limit of expansion imposed by the frequency of failures. The need for more reliable high speed circuits is very real. Much thought and effort is being given to the application of magnetic devices to all types of computer circuits, as one answer to this problem. Concurrent with this effort is the development of new magnetic materials and basic circuits to give these computers even higher speeds. In this Chapter various circuits available to the computer engineer are given, and discussed, in order to indicate the progress that has been made to date.

1. Relays and Switching

Perhaps the most readily recognized feature of a magnetic amplifier is its switching ability, as examination of the representative transfer characteristics show. The first use that comes to mind is a simple a.c. relay, which many computers use by the hundreds. A magnetic amplifier is a non-mechanical, contactless relay. It could even be hermetically sealed for life, and give reliable performance unheard of in the relay field. The only limitation imposed is that the controlled circuit must be able to accept the small magnetizing current which flows at minimum output. Since this current can be made extremely small, with materials available today, this is seldom a disqualifing feature for computer use. Proper design of both the controlled circuit and the magnetic amplifier can, in general, overcome this limitation. This is particularly true where the controlled circuits are magnetic amplifiers of some sort. In

fact, often such a current is desired for one reason or another, and is obtained by shunting the relay contacts. Where a d.c. current is to be controlled, the circuitry becomes more complicated than that of a simple relay, since a magnetic amplifier is an alternating current device. This requires that the a.c. be controlled and then rectified, similiar to the method shown in figure 5-1. This, of course, may not be as generally useful as the a.c. type relay, for some applications.

One illustration of the use of these circuits in switching is the magnetic matrix switch for high speed digital computers (4) (16) (22). One type uses the simplest of magnetic amplifiers, with no diodes, consisting of new type Ferrite cores (M.F.-1118*). A series of cores are arranged as shown in figure 5-2. This a 2^2 position matrix switch. A two digit binary number actuates the flip-flops which bias all the cores but one into saturation. The unsaturated core is the only one which is switched by the driver pulse, when applied. The output can then be applied to a coincident-current memory for write, readout, or rewrite. Larger switches can be obtained by increasing the number of cores. A 2^n position matrix requires 2^n cores, plus flip-flops.

2. Regulators and Servos

One of the first applications of magnetic amplifiers was in the regulation field. This is still one of its outstanding uses today. It can be employed to regulate, with supreme accuracy, voltage, current and frequency. One such application, of interest to computer engineers, is the regulated power supply.

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*General Ceramics and Steatite Corporation, Keasbey, New Jersey

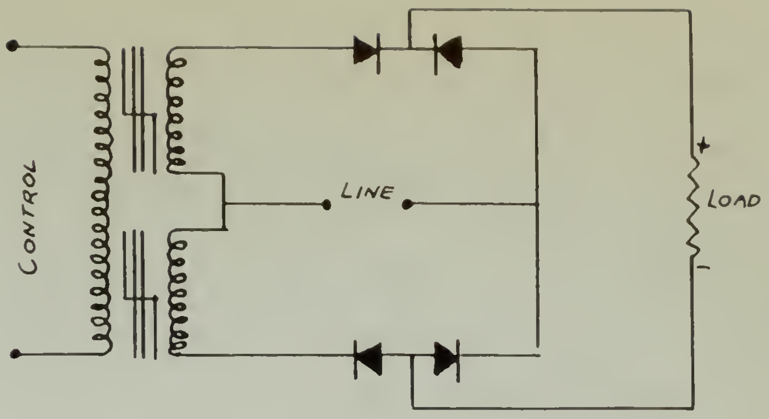
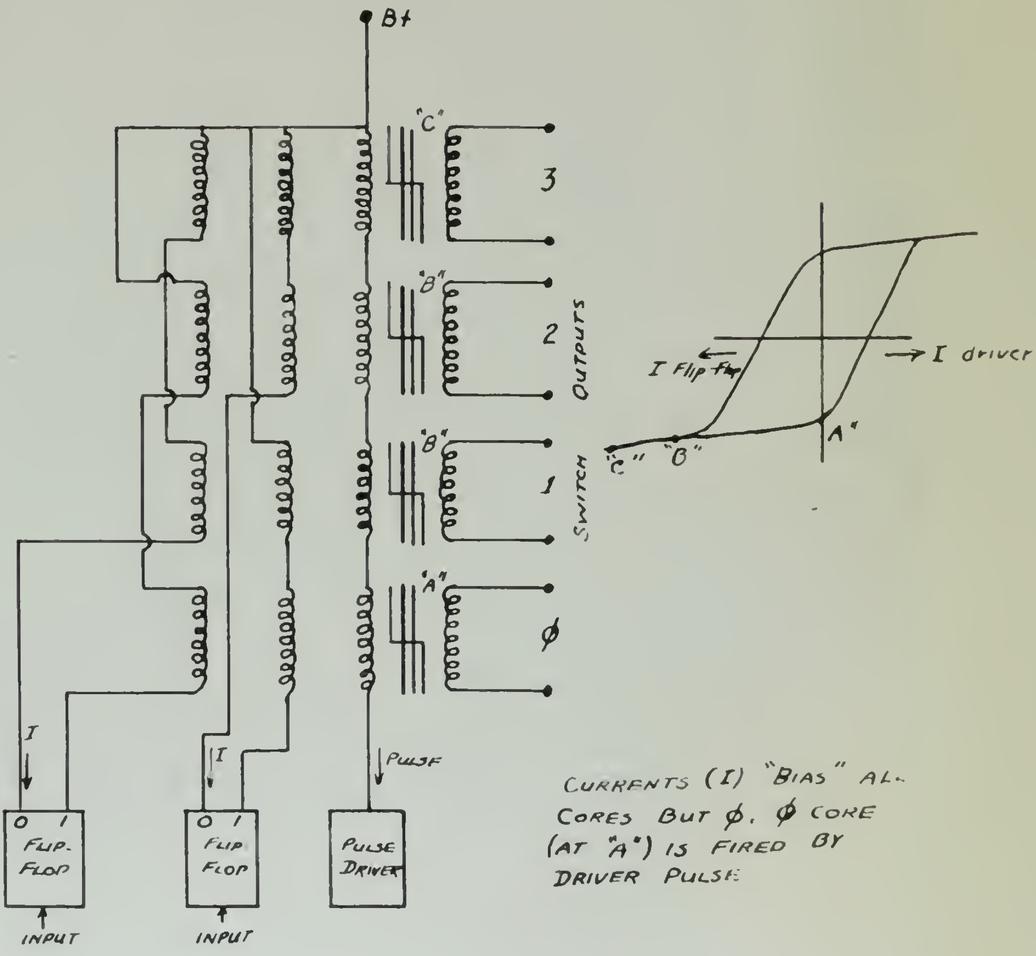


FIGURE 5-1 D.C. OUTPUT MAG/AMP.



CURRENTS (I) "BIAS" ALL CORES BUT φ. φ CORE (AT "A") IS FIRED BY DRIVER PULSE

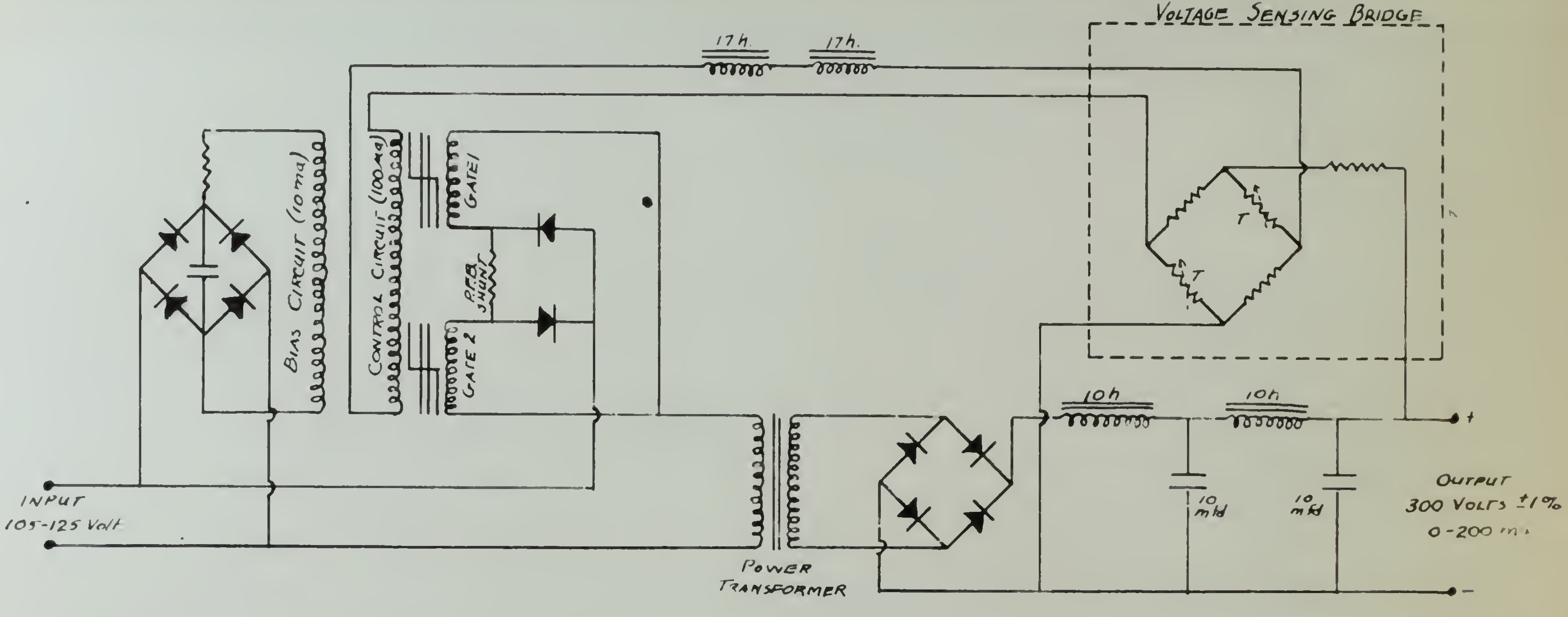
FIGURE 5-2 FOUR POSITION MAGNETIC MATRIX SWITCH.

The equipment shown in figure 5-3 is a simplified diagram of a commerically available regulated supply.* It has a rated output of 300 volts ±1% for a load variation of 0 to 200 ma and a 60 cycle line variation of 105-125 volts. It is also temperature compensated over a wide range of operation, and is completely tubeless. The voltage sensitive detector shown in the block is a non-linear bridge composed of General Electric Thyrites and temperature compensating negative coefficient resistors. The entire unit, with the exception of the diodes and the adjusting resistors are hermetically sealed in Westinghouse potting compound. This equipment can be relied upon to give satisfactory operation for at least 50,000 hours without attention. The limitation of this type regulated supply is its relatively high output impedance at very low audio frequencies, compared to that of the normal tube regulated system.

The diodes used in the circuit of figure 5-3 are rather expensive and large. In order to reduce the number of rectifiers used, the circuit of figure 5-4 has proven satisfactory in preliminary tests. The diodes in this circuit serve the two-fold purpose of rectification and self-saturation for the magnetic amplifier. The equipment constructed had the same ratings as before except that it was operated from a 400 cycle line. As can be seen in the figure, the basic circuit is that of a full-wave voltage doubler, whose inherent regulation is extremely poor. The magnetic amplifier controlled the output within the required 1% with only 10 mfd capacitors.

For small output voltages, the circuit of figure 5-5(a) may be used, this has been called a "flux balance" magnetic amplifier, though all

*Acme Electronics, (Division of Aerovox Corp.) Pasadena, California



"T" DESIGNATES G.E. THYRITE

FIGURE 5-3 REGULATED POWER SUPPLY

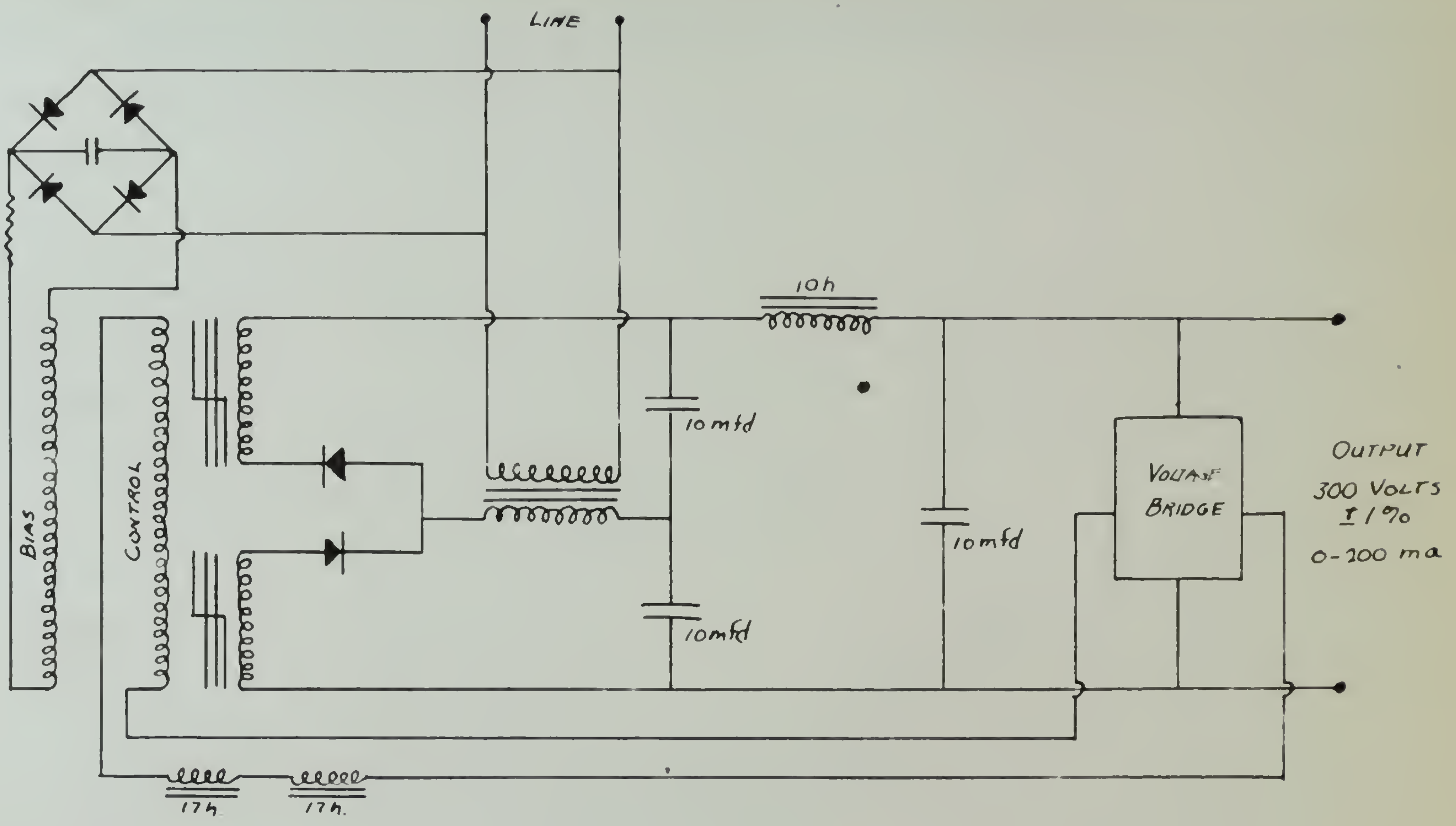
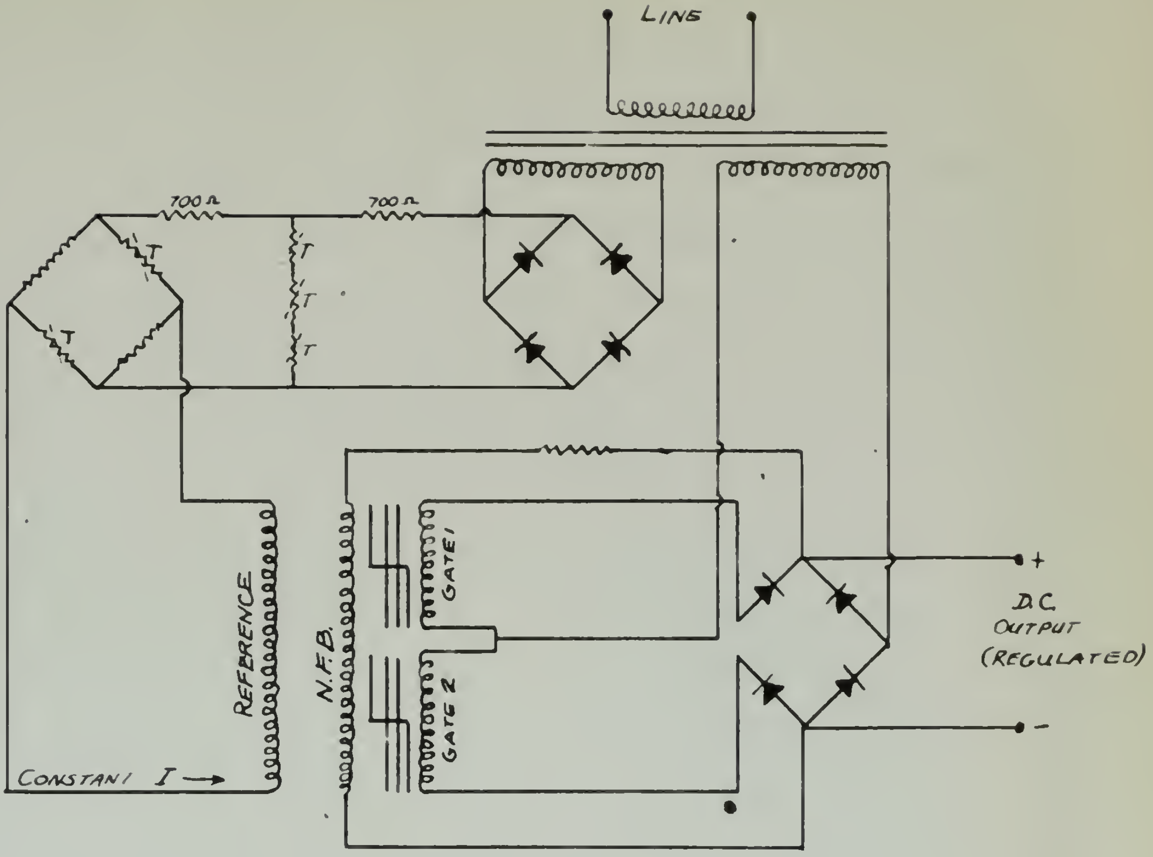
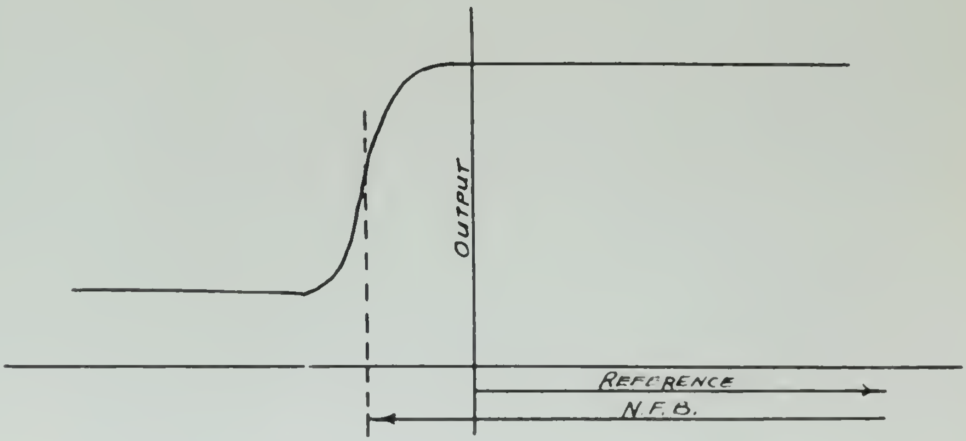


FIGURE 5-4 VOLTAGE DOUBLER REGULATED POWER SUPPLY



(a) CIRCUIT FOR LOW VOLTAGE OUTPUT.



(b) METHOD OF OPERATION

FIGURE 5-5 LOW VOLTAGE REGULATED SUPPLY

mag/amps are flux balance devices in reality. The Thyrite circuit used in this equipment provides an essentially constant current through-out the operating range. The constant NI thus applied to the "reference" winding is balanced, at the operating point on the transfer characteristic, against the output voltage, by means of the negative feedback winding. Now, for example, if the output voltage tends to drop, the current tends to drop, in the NFB winding. This tends to shift the operating point to the right on the transfer characteristic since the feedback is negative. This shift to the right is an increase in output voltage, as may be seen on the curve in figure 5-5(b), thus the output is restored to normal. This is a very accurate regulator. A 10 volt equipment of this type constructed by the author maintained its output within ±0.5% over the entire range of operation (0-500ma). The output was measured to four places on a Leeds and Northrup model K2 Potentiometer. This type circuit makes no pretense of being efficient. It is primarily for use as a very accurate reference source.

The application of magnetic amplifiers to servo systems has received much attention (2) (27). Since its operation is very similiar to a thyatron, it needs no further explanation. The extremely high power gains that can be attained make single stage amplifiers possible to directly control motors from such low level sources as photoelectric cells and thermocouples. Replacement of amplidyne systems, which can be thought of as rotary magnetic amplifiers, is also possible.

3. D.C. Amplifiers

The high gains available with magnetic amplifiers make possible the

construction of drift-free d.c. amplifiers, an extremely useful component for the analog computer. For this operation a d.c. output circuit is used (figure 5-1). The limitations imposed on this circuit, of course, are its rather low input impedance and the response time. The response time can be improved by increasing the power frequency. In any event, the source frequency should be at least twenty times the highest component to be amplified, for linearity. Amplifiers using the Ferramic* cores have been constructed for operation in the megacycle region.

4. Summers

The algebraic addition of currents can be accomplished by simply providing two or more overall control windings on the amplifier, one for each current to be added. The operating point can be adjusted with the bias winding as discussed earlier.

5. Differentiation and Integration

If the input is to be differentiated, the variable voltage need only be applied through a capacitor to the control winding (20). The current is then equal to Cdv/dt and the output, to a first approximation, is proportional to dv/dt. The low input resistance of the winding, in this case, eliminates the need for compensating the IR drop across the resistance as required when tube d.c. amplifiers are used. Both the resistance and inductance of the winding introduce slight errors, however, that must be considered. Accuracies of better than 1% have been obtained with this type circuit. The most serious limitation is that a large capacitor must be used to obtain the necessary input current.

*General Ceramics and Steatite Corporation

Larger capacitors have after effects and leakage which introduces currents not proportional to dv/dt and, hence, errors as great as 3% (20).

Integration can be obtained by feeding back current, through a capacitor, from the output. The positive feedback current is the $C\frac{dVo}{dt}$ where Vo is the output voltage. Making the feedback current equal to the input current;

$$Vo = \frac{1}{c}\int Idt$$

In these circuits, it should be noted that the input and output levels are independent of each other, unlike a tube operated d.c. amplifier.

6. Magnetic Coincidence Counter

Figure 5-6 shows a coincidence counter circuit utilizing single core magnetic amplifier (19). It is basically the same circuit as figure 2-11(a) with several parallel signal circuits. Since the magnetizing current can flow in any one of these circuits, if one of the input voltages happens to be zero the core will reset through that circuit and the output, on the next half cycle, will be zero. When signals exist in all input circuits, the magnetizing current does not flow and the next half cycle of source voltage will produce an output pulse. This pulse is of the correct phasing to operate additional stages, and the power level can be high enough to operate several additional stages. The device is still an amplifier with a power gain of a hundred or more.

7. Magnetic Delay Line and Ring Counter

The diagram of figure 5-7 illustrates the use of the single core device in a magnetic delay line, or ring counter (19). In this circuit the

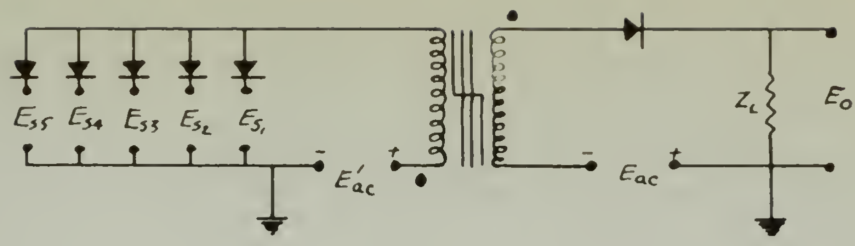


FIGURE 5-6 COINCIDENCE COUNTER CIRCUIT

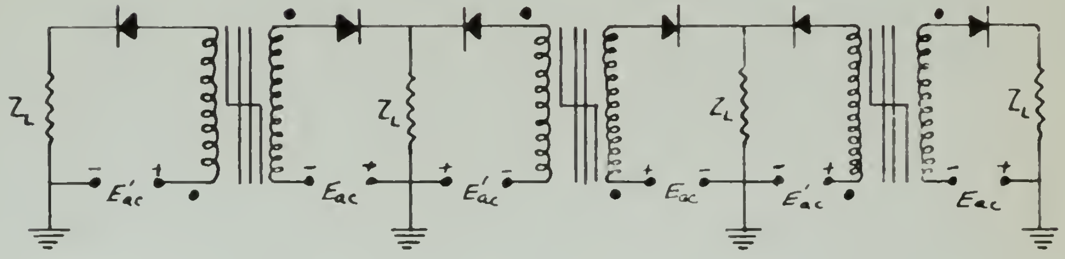


FIGURE 5-7 MAGNET DELAY LINE OR RING COUNTER CIRCUIT

discrete time delay is used to advantage, by cascading stages. The output of one stage operates the input of the next, and so on. Higher gain of course, is not the objective of the cascading. The operation of the line is apparent. The input pulse is reproduced at discrete half cycles by each stage down the line. The total delay in half-cycles equals the number of stages.

To become a ring counter, it is necessary only to connect the output of the last stage to the input of the first. In this case it is necessary to use an even number of stages so that the output of the last stage will occur during a reset half cycle for the first stage. The method of scheduling the ring counter used by Ramey (19) is shown in figure 5-8. This is an "OR" network in which either the output of the final stage "n" or the signal "a" can trigger the first stage. Erasure of either or both pulses can be affected by a signal at "b". Rectifiers r_1 and r_2 prevent excessive currents from flowing in the absence of either signal. This type of coupling could be used between each stage to provide parallel feed and series readout.

8. Magnetic Flip-Flop

A magnetic flip-flop can be constructed by using a two stage ring counter as shown in figure 5-9. In this circuit, no output appears until reset is prevented in one of the cores by a pulse at "a". On following half cycles, the output of one core prevents reset of the other, producing output pulses, until a pulse is applied to "b". When this occurs the pulse from the output is cancelled and reset turns off the flip-flop. There are two output pulses per cycle in this arrangement.

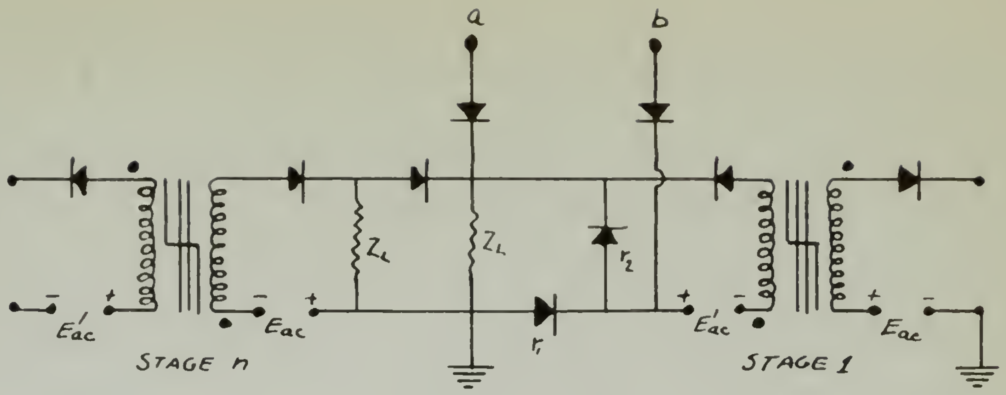


FIGURE 5-8 SCHEDULING CIRCUIT FOR RING COUNTER

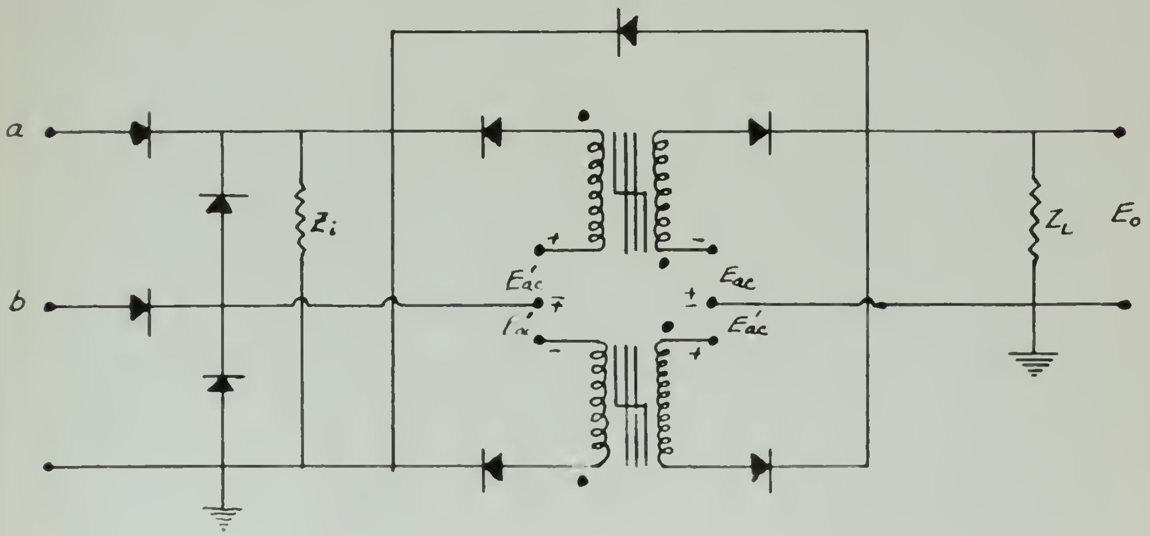


FIGURE 5-9 MAGNETIC FLIP-FLOP

9. Coincident-Current Memory

In addition to the magnetic delay line, another memory unit utilizing magnetic materials has been developed (4) (26). Though this is not a magnetic amplifier, as such, it operates on similiar principles and its speed makes it important in any discussion of magnetic computer elements. This device is designed as a replacement for the electrostatic storage tube in high speed digital computers. It is a much simplier, far more reliable memory than its tube counterpart. It is of the arbitrary-access type, i.e. it does not use time as one of its dependent variables.

Ferrite MF 1118* cores were used to obtain high speed. The flux-current characteristic of such a core is shown in figure 5-10. The positive and negative remanent magnetizations are taken as one and zero states as shown on the curve. The cores are arranged in the manner shown in figure 5-11, a 4 by 4 memory array. For readout, a pulse of $-\frac{I}{2}$ is applied simultaneously to one vertical and one horizontal element. If the "selected" core holds a "one" a large change in flux occurs as shown in figure 5-10. If the core holds a "zero" a small change occurs. Any flux change by any core induces a voltage in the output winding threading each core. Readout always leaves the core in the "zero" state. Write and/or rewrite is accomplished in the same manner, only using $+\frac{I}{2}$ pulses. The cores used allowed a read-out time of five microseconds, with no scanning time required. The unit can be pulsed with a magnetic matrix switch, similiar to that previously described.

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*General Ceramics and Steatite Corp.

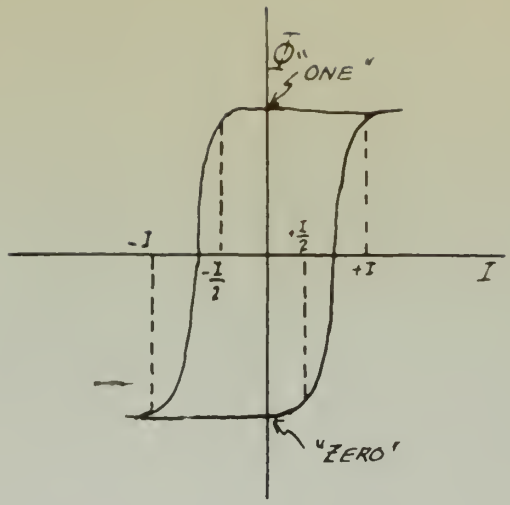

FIGURE 5-10 FLUX-CURRENT CHARACTERISTIC OF MF1118 FERRITE TOROID.

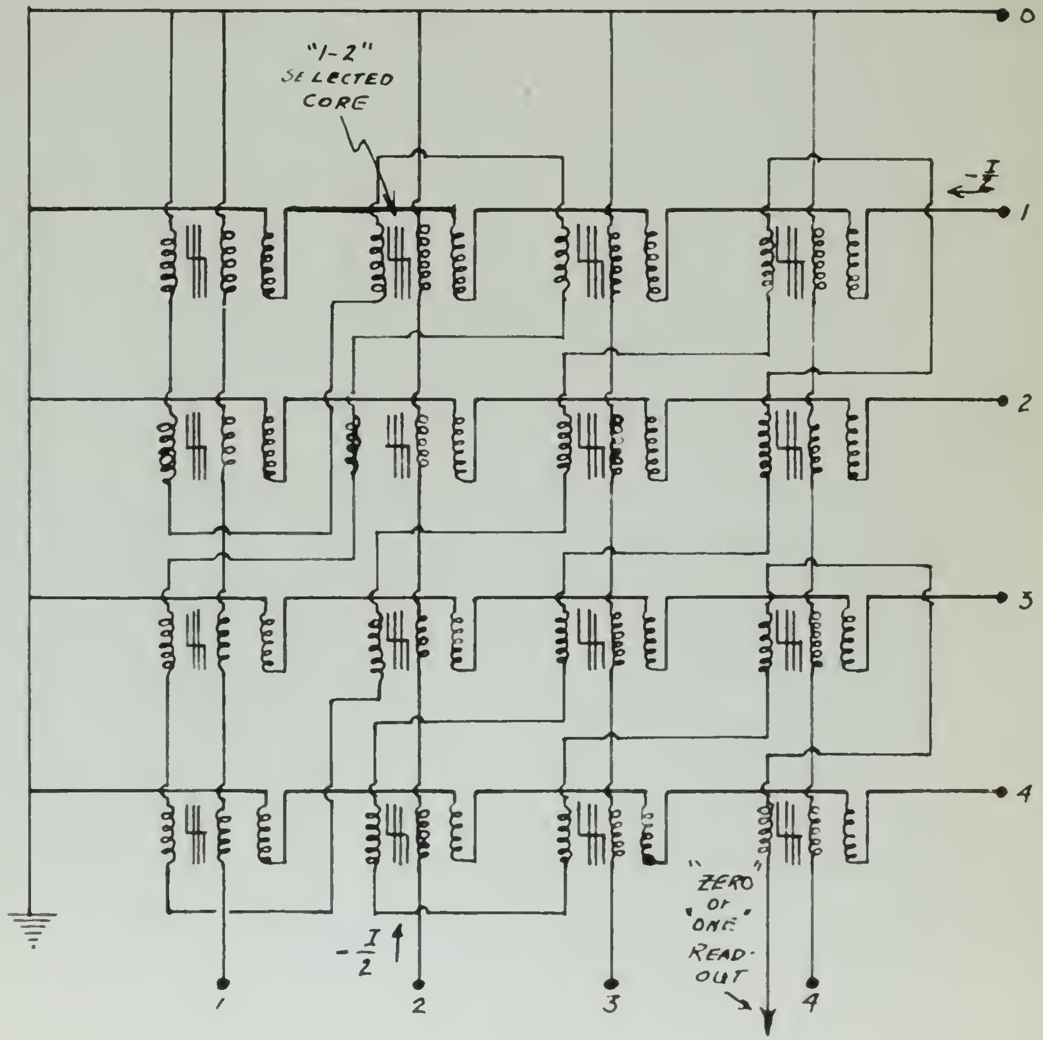

FIGURE 5-11 MAGNETIC COINCIDENT - CURRENT MEMORY

CHAPTER VI

CONCLUSIONS

The reliability of the magnetic amplifier is to be stressed. It is for this reason that they are the subject of considerable interest in the computer field. It has been shown that they possess other fundamental advantages over electron tubes that make them suitable for accepting tasks usually assigned to tubes in computer work. They are not direct replacements for tubes, but, nevertheless, can be made to accomplish jobs similiar to those performed by various tube circuits.

The magnetic amplifier is not without limitations. The application of these devices to analog computers depends upon being able to utilize a rather low input impedance as well as a limited frequency response. For applications requiring high input impedances, it may be possible to utilize a tube for the first stage. By using high frequency power sources, the frequency response can be made high enough for most analog computer applications. The excellent stability, high gain and circuit isolation provided by these devices, together with their long-life, make them excellent analog computer components where-ever they can be used. Their characteristics make them extremely well suited to such applications as airborne and shipboard computers of various specialized types.

The single-core magnetic amplifier appears to be an answer for construction of reliable high-speed digital computers. Their fast and discrete time of response, together with high frequency materials, makes operation at megacycle rates possible. The high frequency oscillator to provide power for this type of operation might be a transistorized

circuit. Magnetic amplifier frequency multipliers are also possible. One type, that has already been constructed, converted 60 cycles to 420 cycles at an efficiency of 60%. This equipment was much lighter than its rotating counterpart (27).

Replacement of special tubes, such as memory tubes, is also possible using magnetic techniques. The coincident-current memory discussed in Chapter V has now been installed in the ENIAC Computer. This has not only improved reliability, but stepped up operation as well. ENIAC now has a memory capacity of 200 numbers, as compared to 20 with the previous tube circuits. It can read in and out at the rate of 50,000 digits per second (26).

The circuits discussed have application to other fields, as well as computers. Some of these applications are quite obvious, while others are not. The output of the coincidence counter, for example, can be arranged as a sampling circuit or as a pulse stretcher and the ring counter can be used as a rotating switch in telemetering circuits.(19).

Although much more development work must be done, the magnetic amplifier has arrived as a computer element. The fact that it already rivals the elctron tube in performance, as well as vastly improving the reliability of equipments, indicate that it will receive much more attention in the field of computers in the future.

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See (27) for more complete bibliography

APPENDIX

Design data for Arnold Engineering Company Deltamax cores

60 Cycles

Core No.	Volts/Turn	Turns/Volt	Bias NI	Window(in^2)
5340-D2	.0034	295	1.18	.15
5515-D2	.0034	295	1.46	.274
4168-D2	.0034	295	2.12	.67
5504-D2	.0076	132	1.76	.35
4635-D2	.01	100	2.22	.675
4179-D2	.01	100	3.4	1.82
5387-D2	.0134	75	2.8	1.09
5233-D2	.02	50	2.36	.675
4178-D2	.027	37	4.25	2.7
4180-D2	.027	37	5.15	4.4
5320-D2	.054	18	3.77	1.54
5468-D2	.11	9.3	5.65	4.4
5581-D2	.243	4.1	7.1	6.3
5582-D2	.41	2.4	9.2	6.7
5579-D2	.11	9.3	8.6	12.5

400 Cycles

5340-D2	.0228	44	1.96	.15
5515-D2	.0228	44	2.44	.274
4168-D2	.0228	44	3.54	.67
5504-D2	.051	19.7	2.94	.35
4635-D2	.067	15	3.73	.675
4179-D2	.067	15	5.65	1.82
5387-D2	.09	12.2	4.7	1.09
5233-D2	.134	7.5	3.93	.675
4178-D2	.18	5.5	7.06	2.7
4180-D2	.18	5.5	8.6	4.4
5320-D2	.36	2.7	6.28	1.54
5468-D2	.735	1.4	9.4	4.4
5581-D2	1.63	.61	11.8	6.3
5582-D2	2.74	.36	15.3	6.7
5579-D2	.735	1.4	14.3	12.5

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